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MAGNETICALLY SUSPENDED FLYWHEEL SYSTEM STUDY

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ABSTRACT

The Goddard Space Flight Center (GSFC) and the University of Maryland (UM) Mechanical Engineering Department have a common interest in flywheels and have cooperated since the mid-1970's in designing and testing flywheel components. GSFC/UM is currently involved in studying application of a graphite/epoxy, magnetically suspended, pierced disk flywheel for the combined function of spacecraft attitude control and energy storage (ACES).

Past achievements of the GSFC/UM magnetically suspended flywheel program include design and analysis computer codes for the flywheel rotor, a magnetically suspended flywheel model, and graphite/epoxy rotor rings that have been successfully prestressed via interference assembly. All hardware has successfully demonstrated operation of the necessary subsystems which form a complete ACES design.

Areas of future GSFC/UM work include additional rotor design research, system definition and control strategies, prototype developement, and design/construction of a UM/GSFC spin test facility.

The results of applying design and analysis computer codes to a magnetically suspended interference assembled rotor show specific energy densities of 42 Wh/lb (92.4 Wh/kg) are obtained for a 1.6 kWh system.

INTRODUCTION

The Goddard Space Flight Center has been active in the development of high efficiency motor/generator and magnetic suspension systems since the early 1960's. One outcome of this work resulted in a magnetically suspended momentum wheel for spacecraft application [1,2,3]*.

Based upon this early work at GSFC it appeared useful to consider a system which can provide for the joint functions of attitude control and energy storage. Since the mid-1970's GSFC and the University of Maryland have been active in a joint program on the various aspects of a magnetically suspended flywheel system. Recently GSFC/UM has addressed the problems of the joint solution of attitude control and energy storage. The program is termed ACES (Attitude Control and Energy Storage) and it involves hardware definition and problem identification/solution of all aspects of a magnetically suspended flywheel system.

The purpose of this paper is to provide a brief review of the GSFC/UM ACES effort, to present some of the hardware currently undergoing testing, and to identify the areas of future work.

* Brackets denote references at end of paper.

SYSTEMS BACKGROUND

In designing a magnetically suspended flywheel system, GSFC/UM has concluded [4,5,6] that a pierced disk of uniform thickness provides a desirable rotor geometry from both a performance and manufacturing point of view.

Shown in Figure 1 is a cross-sectional view of the original GSFC/UM magnetically suspended flywheel design. The original design consists of 2 rings with the outermost ring being made of a filamentary wound composite material and the inner ring being made of continuous iron bonded to the filamentary wound ring. The stator of this design fits in the "hole" of the 2 ring rotor and it carries the magnetic suspension and motor/generator electronics. The original GSFC/UM design was configured around a homopolar permanent magnet motor/generator with variable field flux for maintaining constant voltage output as rotational speed varies [4]. The magnetic suspension system is an integral part of the motor/generator design and it utilizes permanent magnets to establish a steady state magnetic flux, which is then modulated via sensor feedback [4].

Shown in Figure 2 is a photograph of the current test system which GSFC/UM is using to establish rotational losses and efficiencies for the motor/generator and magnetic suspension concepts embodied in the original GSFC/UM design. Testing is currently under way on this first generation ACES design and preliminary results are encouraging and support the performance projections previously presented in the literature [4,6].

ROTOR DESIGN CONSIDERATIONS

RCA [7] and J.A. Kirk, under contract to GSFC, have done additional work on the original GSFC/UM design. It was concluded that a multiring, interference assembled rotor, such as shown in Figure 3, would provide for substantial improvements over the original GSFC/UM design. The modified GSFC/UM design, shown in Figure 3, differs from the original GSFC/UM design in the following areas:

1. The rotor is composed of a number of individual filamentary wound rings, rather than being one continuous ring.
2. The inside diameter (ID) to outside diameter (OD) rotor ratio (ID/OD) is smaller than the original GSFC/UM design.
3. The innermost ring is made of iron and is segmented into discrete pie-shaped "chunks".

Each of the above changes was made in the original GSFC/UM design in order to improve the overall performance of the system. The reasoning behind the changes has been documented by Kirk and Huntington [8,9,10,11] and a brief explanation follows:

1. The rotor is made of a number of composite material rings which are interference assembled. The reason behind this change is to favorably prestress the rotor so higher rotational speeds and energy densities can be obtained before a limiting performance constraint is encountered.
2. The ID/OD ratio has been lowered. The reason behind this change is that the original GSFC design was of a "thin hoop" type and suffered excessive "gap" growth between the rotor and the stator as it spun.

Since gap growth will degrade electrical performance, it must be controlled, and the best way to achieve this control is by decreasing the ID/OD ratio.

3. The innermost ring must be made of iron and is now segmented instead of being continuous. This change has been made because the iron ring would always reach its limiting strength long before the filamentary wound composite ring(s) reached their strength limit. To overcome this limitation a "segmented" inner ring is now proposed for use on the magnetically suspended flywheel system. The important point to note is that the inner iron ring will have all the necessary magnetic properties but will consist of a number of pie-shaped segments which are bonded to the inside diameter of the first filamentary wound ring. The iron ring thus has no stiffness in a "hoop" or tangential direction and presents an "inner loading" on the filamentary wound composite ring to which it is attached.

The three changes described above have no impact on the motor/generator or magnetic suspension system. The effect that these changes have on the projected system performance is dramatic and has been documented via a recent GSFC contractor report [12].

ROTOR ANALYSIS TOOLS

GSFC/UM realize that the final rotor design dimensions must evolve in parallel with the magnetic suspension and motor generator designs (as they impact on the dimensions and weight of iron inner ring). Obviously then, the most useful rotor design and analysis tools are those which most closely model the real physical system and are convenient to apply as the iron inner ring design evolves. GSFC/UM has developed two (2) design and analysis tools for this purpose. Both tools are computer codes which perform detailed stress analysis and final dimension selection (including component tolerances) for all the components of the ring rotor. The analysis code is called FLYANS (FLYwheel ANalySis) and the sizing code is called FLYSIZE (FLYwheel SIZE). The interested reader will find a description of these codes in References 8 and 12.

Shown in Figure 4 is a schematic diagram of the multiring rotor which is modeled by the FLYANS and FLYSIZE codes. Each of the rotor rings is the same axial thickness and the stresses in each ring consist of a hoop or tangential stress (σ_θ) and a radial stress (σ_r). If power is being put in or taken out of the system there is an additional shear stress ($\tau_{r\theta}$) in each ring. It is assumed that the flywheel rings are in a state of plane stress, meaning that there is no variation of the σ_θ and σ_r stresses in the axial direction.

The materials which comprise the multiring rotor are modeled as homogeneous, linearly elastic, orthotropic materials [13], with material properties specified in the radial and tangential direction. The current GSFC/UM design is based on Celion 6000/epoxy for the filamentary wound composite rings [12]. It should also be pointed out that any new or hypothetical materials can easily be added to the computer code data base with minimal effort.

The total stress distribution in one ring of the multiring flywheel is the superposition of the five stress distributions due to the following:

1. Rotation of the ring at constant angular velocity.
2. Interaction with adjoining rings due to rotational expansion.

3. Interference assembly of the rings.

4. Residual stresses due to curing.

5. Angular acceleration of the entire assembly.

The stress distribution for the entire flywheel is the summation of the above 5 stresses for each flywheel ring.

Of the 5 stress distributions given above, no. 3, interference assembly, is under the direct control of the designer. The FLYANS code provides an algorithm for the selection of interference pressures in order to optimize the stored energy per unit weight of the rotor.

It will be instructive at this point to consider the hypothetical example of how interference stresses interact with rotational stresses in a simple 2 ring "pierced disk" rotor.

Shown in Figure 5 is the stress distribution which occurs when 2 rings of the same material are interference assembled. When the interference stress distribution is added to the rotational stress distribution the net result is as shown in Figure 6. In Figure 6 the stresses have been made nondimensional by the factor

$$\rho_1 \omega^2 b^2 \text{ (units are psi)}$$

where

ρ_1 = mass density for the first ring of the assembly (value is weight density in lb/in^3 divided by $g = 386\ in/sec^2$)

ω = rotational speed (rad/sec)

b = outer radius of the flywheel (inches)

The solid line shown in each of the plots in Figure 6 represents the stress distribution which occurs when the 2 rings are spun without any interference assembly present. The dotted lines show the stress distribution when the 2 rings are interference assembled and then spun. Consider the lower plot in Figure 6. If the working tangential stress of the material, σ_θ, is constant, then the limiting value of $\sigma_\theta/\rho_1\omega^2b^2$ is ≈ 0.97 with no interference present, and 0.94 with interference present. For a fixed value of b and σ_θ it is clear the interference assembled flywheel has a larger ω, and therefore a larger kinetic energy per unit weight over the non-interference assembled flywheel.

GSFC/UM has done preliminary testing of interference assembly of composite rings and has found that a conical taper of approximately 1 degree between the inside diameter and outside diameter of adjacent rings will permit press assembly of the rings. Shown in Figure 7 are two graphite epoxy rings that were assembled and pressed together at the Hercules Alleghany Ballistics Laboratory (Cumberland, MD) in 1978. The two rings are 8 inches in OD, 7 inches in ID and are each 1/2 inch in radial thickness. The two rings have approximately 0.3% interference and the ring interface was lubricated with epoxy before pressing together. The collection of wires shown in Figure 7 is for strain gage instrumentation placed on the rings. The ring assembly shown in Figure 7 was donated to the University of Maryland and is currently undergoing further testing as part of the GSFC/UM ACES program.

The results of applying the FLYANS and FLYSIZE computer codes to a 1.6 kWh GSFC/UM design [12] have shown that it is possible to design a 6 ring rotor with an iron inner ring. The rotor has an inside diameter of 8 inches and an outside diameter of 20 inches. Using Celion 6000/epoxy for all the filamentary wound composite material rings, the projected specific energy density is 41.9 Wh/lb

(92.2 Wh/kg) and the inner radius displacement (i.e., air gap growth) will not exceed .040 inch (from 0 to burst speed).

CURRENT WORK

GSFC and UM are currently engaged in a detailed study which will significantly advance understanding of the magnetically suspended flywheel for ACES. The following three major tasks are currently being worked on:

1. Rim research requirements
2. Systems research requirements
3. UM/GSFC prototype development and spin test facility.

Task 1: Rim Research Requirements

The purpose of this task is to conduct a detailed analytical analysis of the mechanical properties and stresses of a composite material rim. Specifically the analysis will include:

- Analytical determination of the stress distribution in the rim. This will include the loading of the iron at the inner radius. The simulation of the stress distribution will be initially represented by closed form solutions, although standard finite element codes may be applied if the authors feel their use is warranted.
- Determination of the effect of mechanical stresses on the magnetic properties of the iron with specific consideration of hysteresis.
- Identification of optimum materials and manufacturing/assembly methods for present and future rims with an aim towards maximizing performance.
- The use of multirings that are interference assembled for prestressing.
- Identification of detection mechanisms for rotor failure and system

shutdown prior to destructive failure.

The overall goal is to clearly define the present state of technology and future problems that must be solved for a viable design.

Task 2: System Research Requirements

The purpose of this task is to conduct a study in order to establish the feasibility of the complete ACES system. Three major sub-tasks have been identified. These are:

- System definition
- Control strategies
- System testing

System definition includes the characterization of the subsystems needed for the entire system. This includes specifying, at least generally, the requirements of commutation, microprocessing, containment and interactions, and identifying the problems of failure and shutdown. The identification of control strategies for the system is quite unique. Certainly the inertial coupling and control of the momentum require careful analysis. The interaction of the magnetic field and other perturbations on stability and attitude control are also important areas requiring careful characterization.

The system testing component of this task is specifically concerned with testing the GSFC/UM model. This model will be modified for maximum performance by redesigning the rotor initially. The primary thrust of this exercise is to identify important parameters that must be studied for future component and system design.

Task 3: UM/GSFC Prototype Development and Spin Test Facility

An important adjunct to the current research tasks is to foster continued long-term involvement between the University of Maryland and GSFC. At the end of FY 84 it is envisioned that GSFC/NASA Headquarters will continue UM funding for development of the ACES system. In particular, the next phase of the work will involve development of a 500 watt hour ACES system along with design and construction of test facilities suitable for evaluating the 500 watt hour system. The proposed UM test facilities will provide for experimental monitoring of the performance of the rim, motor/generator, and magnetic suspension systems. The 500 watt hour system will be designed for ease in the replacement of all components. It is expected that the 500 watt hour system will serve the purpose of both a showpiece working model and a facility to try out enhancements which can improve system performance. Not only will UM be a NASA/GSFC resource but, in addition to that, NASA contractors producing deliverable magnetically suspended flywheel systems will find UM to be a valuable analysis, test, and evaluation facility.

CONCLUSIONS

The concept of using a magnetically suspended flywheel for the combined function of spacecraft attitude control and energy storage (ACES) is extremely viable. Several pieces of hardware have been built and are undergoing testing to evaluate the various subsystems used in ACES. Based upon reasonable and well founded projections, an ACES magnetically suspended flywheel system could easily store 1.6 kWh with a rotor specific energy density of 42 Wh/lb (92.2 Wh/kg).

The areas of study which will be required to integrate the ACES subsystems into a complete working system have been identified and are currently under detailed study. The results of the current study will project a workable

5-year plan between UM and NASA/GSFC to turn the already documented successes of the magnetically suspended flywheel system into a complete ACES system.

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Figure 1

Original GSFC/UM Design

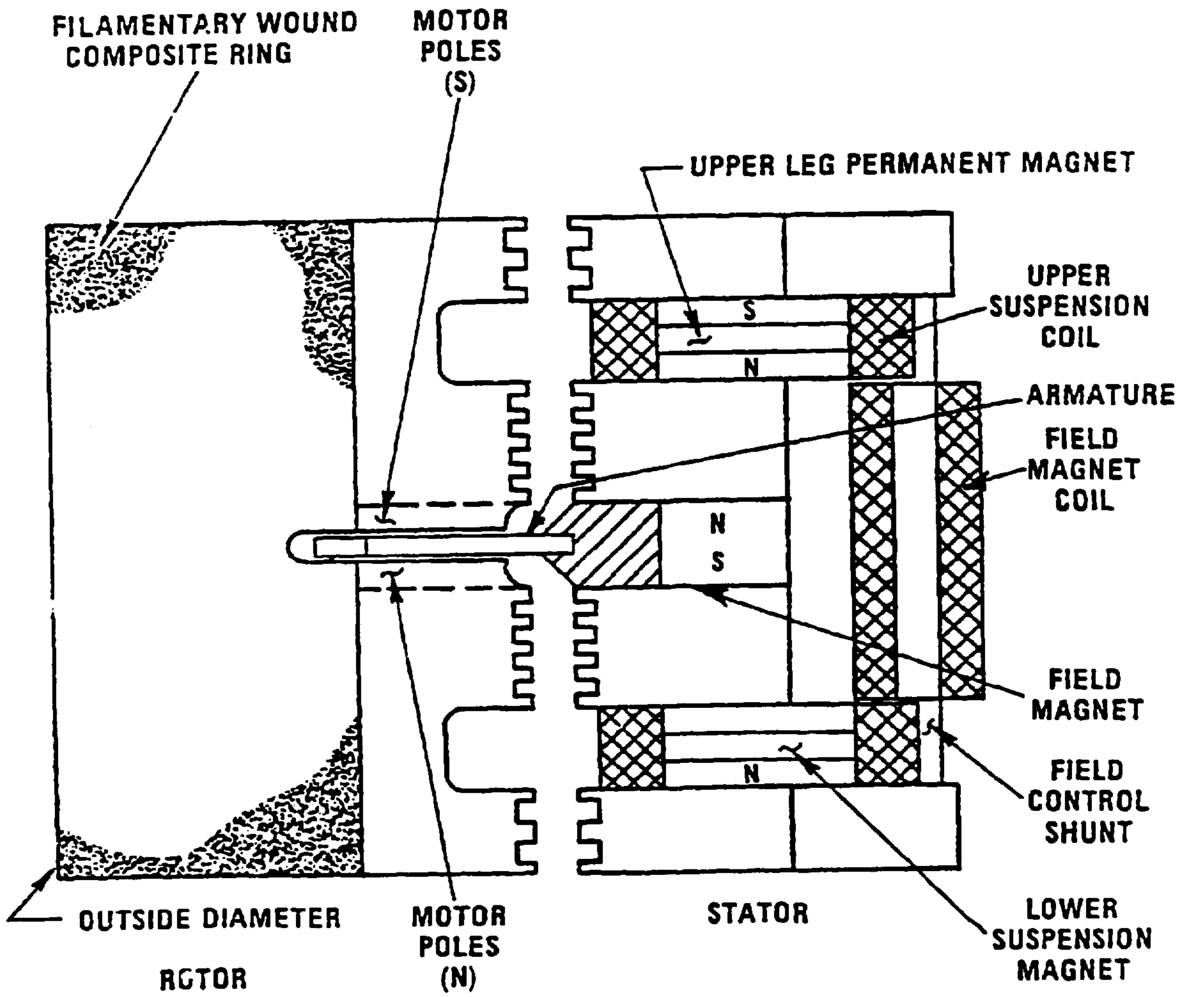

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Figure 2

The GSFC/UM test system

Figure 3

Modified GSFC/UM Design

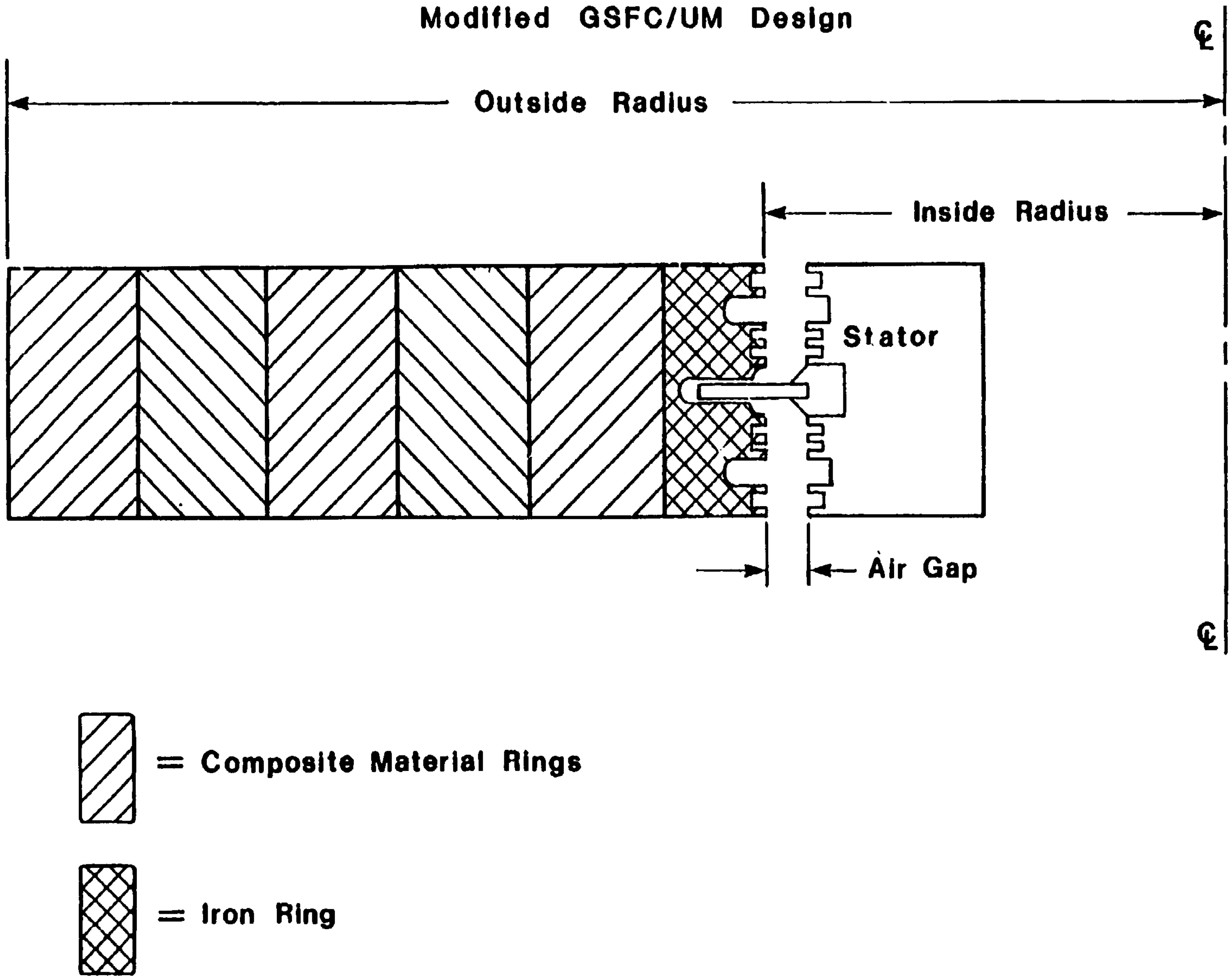


Figure 4

Ring Rotor Model

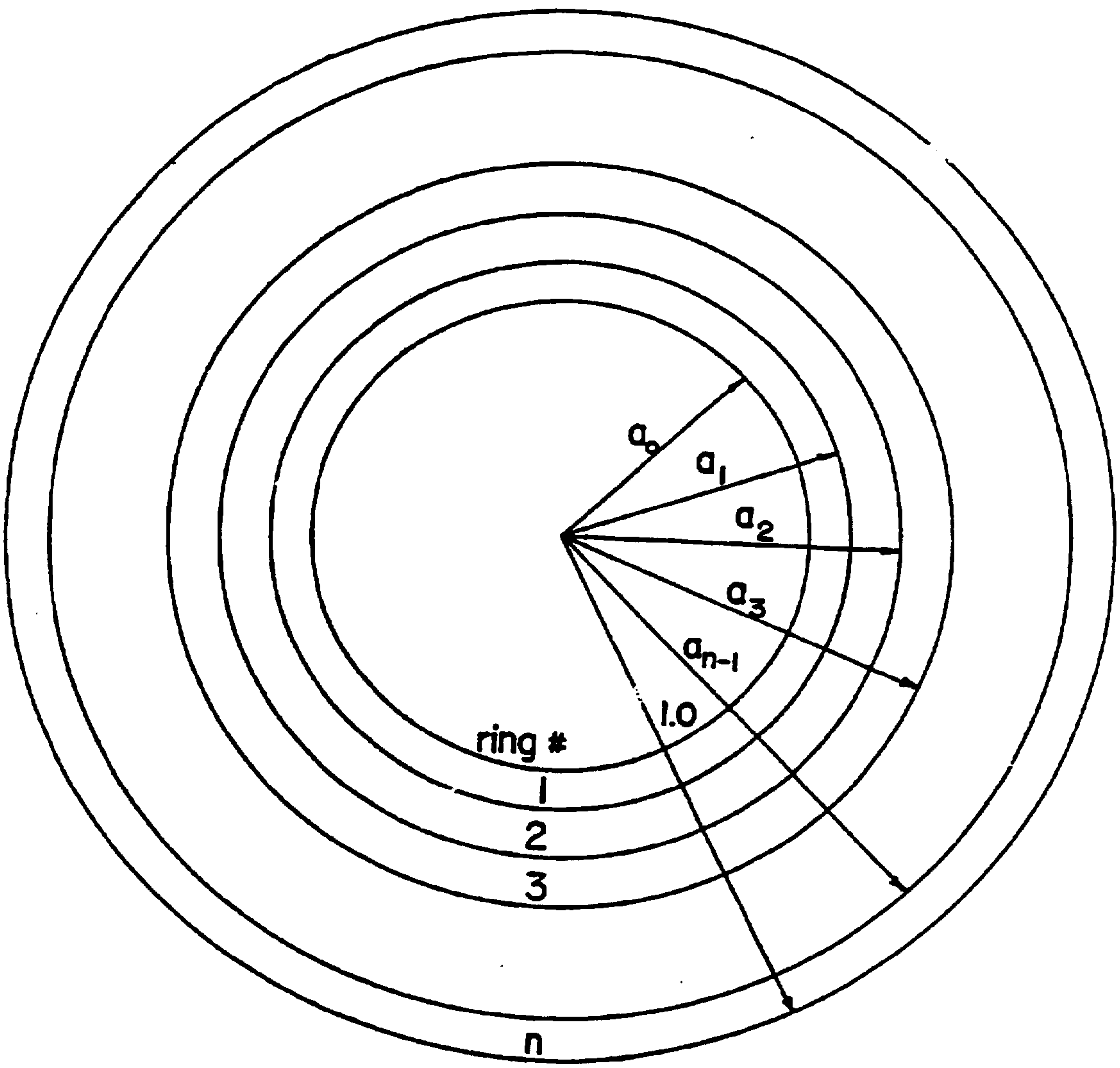
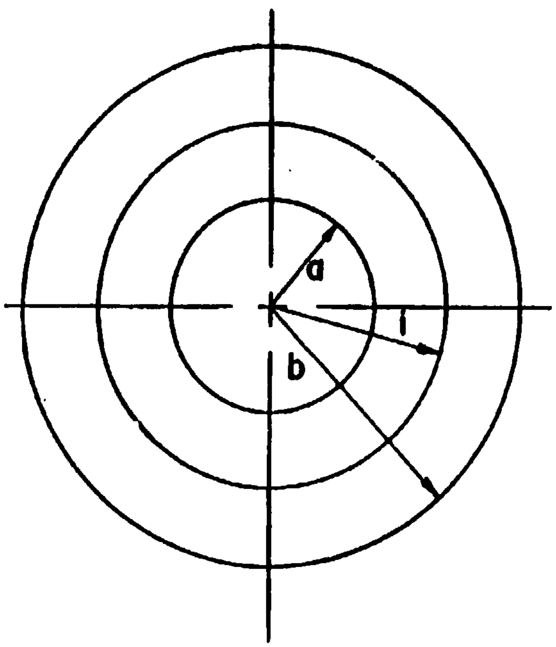
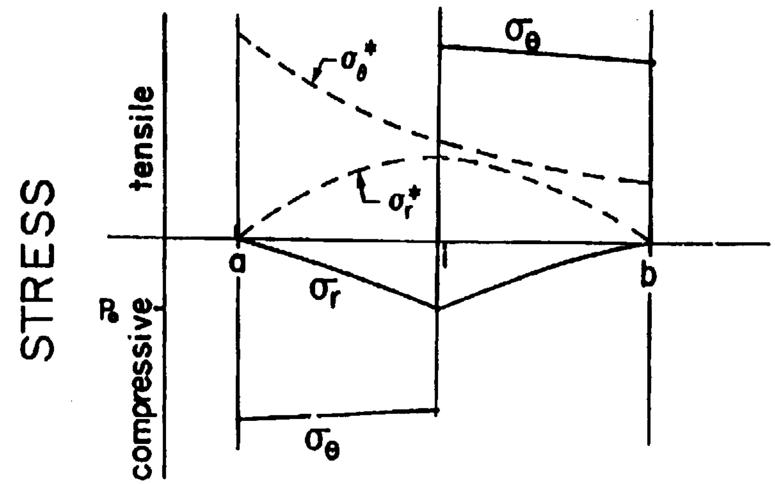


Figure 5

INTERFERENCE ASSEMBLY

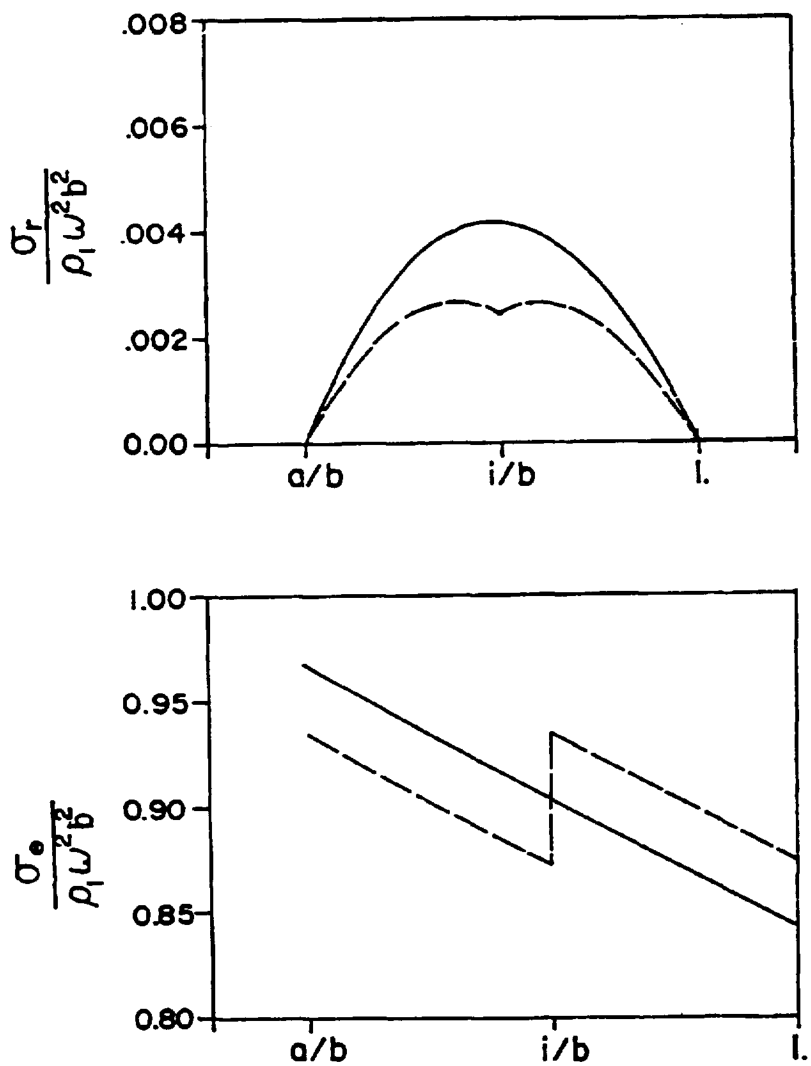




σ_θ^*, σ_r^* – Rotational Stresses

Figure 6

STRESS VS. RADIUS
2 RING



——— = No Interference

– – – – = With Interference

Figure 7

Graphite/epoxy press fit rings